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The concept of a prefabricated structure for protection of critical infrastructure facilities

KAMIL SOBCZYK, RYSZARD CHMIELEWSKI, KRZYSZTOF DUDA

Military University of Technology, Faculty of Civil Engineering and Geodesy,
Department of Military and Transport Construction Engineering,
2 Gen. W. Urbanowicza Str., 00-908 Warsaw, Poland, kamil.sobczyk@wat.edu.pl,
ryszard.chmielewski@wat.edu.pl, krzysztof.duda@wat.edu.pl

Abstract. The paper presents the concept of a protective structure in the form of a prefabricated reinforced concrete protective dome intended for protection of a single critical infrastructure facility [1]. Unlike non-movable cast-in-place reinforced concrete structures, the protective structure can be assembled and disassembled repeatedly with the use of dedicated joining sockets. To provide the concept with a high mobility, the dimensions of single modules of the prefabricated reinforced concrete protective dome meet the transport limits dictated by the horizontal and vertical clearance of roads. A numerical computational analysis facilitated a determination of the distribution of internal forces in the protective stricture and dimensioning of the required reinforcement system [3]. The computations included standardized cases of steady and dynamic loads, and combinations thereof, complete with parameters of dynamic loads from an explosion impulse.
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1. Introduction

Protective structures dedicated to technical equipment, personnel units and facilities in critical infrastructure areas are very important assets during peace and war. Protective structures are designed to provide the security level required against specific military and non-military threats which can occur in hybrid war scenarios. Protective structures have become an urgent topic of diverse analyses due to the increasing significance of terrorism in the modern world (and in Europe) and the recent global climatic change, which have severely afflicted the territory of Poland. A challenge regarding protective structures is that they require an adequate and proper approach to enable their emergency deployment in the shortest time possible. A conclusion can be made that it would be prudent, given the requirements of national security, to have ready-to-use protective structures available for immediate deployment in all terrain conditions.

2. Definition of critical infrastructure

Critical infrastructure (CI) is key to national security, stable economic growth and the proper functioning of society of a state. The increasing importance of national CI facilities and systems is related to the maintenance of unobstructed functioning of the country in the face of modern threats. It is of utmost importance to apply measures for the effective security of the CI by its protection.

The experiences which have been obtained from actual crisis emergencies to date dictate that security protection is especially required for underground fuel depot tanks (Fig. 2.1), fuel pumping stations, water intakes, public telephone exchange facilities, telecommunication equipment and systems, grid transformer substations, stationary command posts, munition stores, radiolocation units, natural gas transmission pressure reducing stations (Fig. 2.2), and telecommunication system control equipment.

Fig. 2.1. Underground fuel Fig. 2.2. NG pressure reducing depot tanks [7] and metering station [7]

3. Potential threats to the security of critical infrastructure

A threat can be construed as a likely emergence of conditions hazardous to the environment at the emergency site, as well as to a specific CI facility or component. A risk analysis related to CI may include a specific classification of categories and groups of threats which may affect the CI system components under analysis [2].

1) Category One: Threats from natural disasters:
   - floods;
   - landslides;
   - windstorms, hurricanes and whirlwinds;
   - extremely low temperatures; blizzards with blowing and drifting of snow.
2) Category Two: Threats from intentional human activity:
   - intentional military and/or terrorist activities;
   - economic and political threats.
3) Category Three: Threats from inadvertent human activity:
   - structural defects in CI facilities and installations;
   - improper operation and/or maintenance of CI equipment.

If special security protection requirements are identified during the design and mission analysis of a CI component, the most likely solution for the requirement is a protective structure (a bunker or a shelter). Protective structures provide suitable security of extremely mission-critical components of CI or personal protection. Stationary solutions of protective structures may include purpose-designed hardened aircraft shelters (which are currently operated at airfields as protective structures for aircraft and other military equipment).

It would be possible to use temporary protective structures in a crisis emergency where the emergency response time is limited; the protective structures would provide the required level of specific (visual, ballistic, and/or weather) protection in a very short time. It would be then necessary to develop a novel type of protective structure to meet the modern demands of protection value, construction time, and reusability.

4. The concept of a novel protective structure

No widely or easily available protective structure exists on the Polish market today which would be dedicated to small CI system components, highly mobile, and easily deployed and removed. The existing structural solutions, namely shelters, bunkers, or hardened aircraft shelters are time-consuming in terms of deployment (construction) and are permanent structures (immobile).

There is a need for development of a novel protective structure which would cover the demand for mobility and ease of (quick) deployment and removal. The structural solution conforming to the concept proposed herein is a prefabricated protective dome deployed on an intermediate foundation and currently under patent protection [1]. Many CI facilities feature no effective ballistic, electromagnetic and/or explosive protection. In the event of a ballistic, electromagnetic or explosive threat, the CI facilities are exposed to direct effects of projectile impact or the pressure wave and heat from an explosion, e.g. of an IED.

Pursuant to this concept, the prefabricated protective dome will be assembled from prefabricated components (made of composites or concrete) with standard construction machinery and equipment, irrespective of the deployment location conditions (including soil and water) [1].

The prefabricated protective dome modules are joined with a system which facilitates repeated assembly and disassembly of the whole protective structure. Dedicated joining sockets at the designed joints of individual prefabricated protective dome modules are used for fastening the prefabricated dome modules together. The joining sockets are designed according to the following orientation principle:

- female sockets along the parallel joint edges;
- male sockets along the oblique joint edges.

A schematic of the concept is shown in Fig. 4.1.

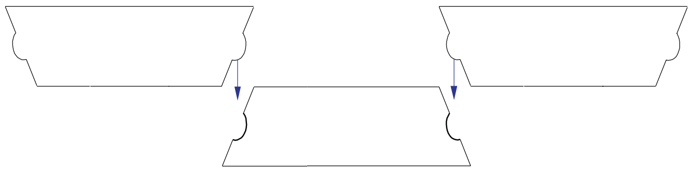

Fig. 4.1. Assembly of prefabricated protective dome modules with the joining sockets [1]

The following is a diagram of a large prefabricated protective dome, 32 metres in diameter, which can be deployed to secure fuel depot tanks with a capacity of thousands of cubic metres or shelter combat aircraft. The prefabricated protective dome is made of over thirty prefabricated modules in five different forms. A prefabricated protective dome conforming to this concept can be deployed with the centre elongated with the segments assembled from the largest prefabricated modules; here, the number of the segments should be odd. A schematic of the prefabricated protective dome structure is shown in Fig. 4.2.

Large-scale CI facilities can be sheltered with prefabricated protective domes deployed open on one side by removal of selected Form Type 2 to 5 prefabricated modules.

The assembly of a prefabricated protective dome requires two mobile cranes and features the following operations:

— deployment of two Form Type 1 modules;
— addition of two Form Type 2 modules;
— addition of four Form Type 3 modules, with two on opposite sides simultaneously;
— addition of eight Form Type 4 modules, with two on opposite sides simultaneously; the next two are arranged and installed in parallel to the first two in already place, and this operation is repeated two more times;

— addition of sixteen Form Type 5 modules, with two on opposite sides simultaneously; the next two are arranged and installed in parallel to the first two in already place, and this operation is repeated four more times.

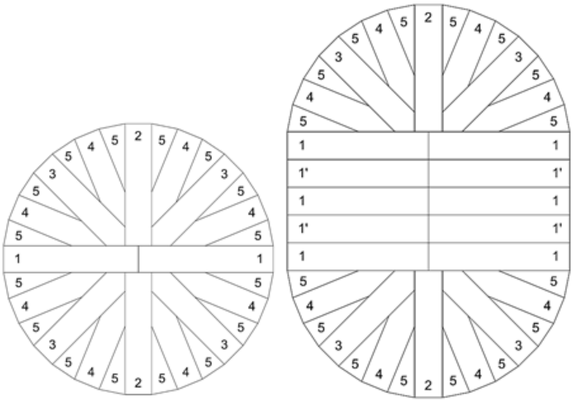

Fig. 4.2. Arrangement diagram of a large prefabricated protective dome: (a) basic arrangement; (b) elongated dome arrangement [1]

Smaller prefabricated protective domes can be built according to the concept for sheltering smaller CI components. Examples of shelterable facilities include jet fuel tanks, single vehicles, or a hardened personnel shelter. What follows is an analysis of a medium-sized prefabricated protective dome with a diameter of 16.0 m.

5. Analysis of a medium-sized protective structure

One of the objectives of the protective structure concept contemplated in this work is effective protection of fuel depots, which generally comprise jet fuel tanks. The medium-sized prefabricated protective dome can serve just as well as a hardened shelter for military personnel and technical equipment. The basic dimensions of the CI component to be protected were adopted from a Leopard 2A5 main battle tank, the basic tactical and technical specifications of which are listed in Table 5.1 [7].

Table 5.1

Basic geometrical data of the Leopard 2A5 main battle tank [7]

Overall length	9.67 m
Hull length	7.72 m
Overall width	3.76 m
Turret ceiling height	2.64 m
Overall height	3.03 m

A prefabricated protective dome with a base diameter of 16 m and a top height of 5.12 m (including the sectional thickness of 0.24 m), the cross-section of the sheltered vehicle and the cross-section of the dome are shown in the diagram in Fig. 5.1.

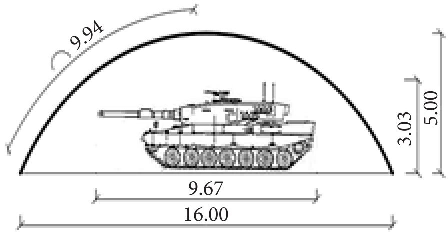

Fig. 5.1. Cross-sectional diagram of the medium-sized dome

5.1. Computational model

To carry out the analysis of the prefabricated protective dome, a numerical computational model was developed in Autodesk Robot Structural Analysis, a FEM software solution. It was decided to design the computational model as a three-dimensional mesh structure. Form Type 1, 2 and 3 modules of the prefabricated protective dome were chosen as critical for the structure. Form Type 4 and 5 modules carried the load on the three main module form types. The modules were designed as an arched reinforced concrete beam and a trapezoid cross-section profile was introduced into the computational model, see Fig. 4.1. A prefabricated intermediate foundation structure was developed for the computational model, which rested on the former on pinned supports.

5.2. Loads

The loads included in the model were the dead weight of the structure, the weight of a 0.5 m thick fill, and the standard climatic wind and snow loads [].

The dead weight of the structure was included automatically by the input of the designed cross-sections of the mesh bars, which were 24 cm thick.

The fill was intended to provide additional camouflage and additional ballistic and explosion protection. The fill conformed to medium-grained damp sand with minimum compaction and at a bulk density of 18.5 kN/m^3.

The wind thrust pressure was determined according to the Eurocode wind load standard [9]. The external pressure values were read according to the diagram in Fig. 7.12 of the reference standard for the following:

— Area A → $c_{pe,10}\left(\frac{h}{d}=0\right)=+0,6;$;

— Area B → $c_{pe,10}\left(\frac{h}{d}=0\right)=-0,9;$

— Area C → $c_{pe,10}\left(\frac{h}{d}=0\right)=0.$

Once included, the external pressure $c_{pe,10}$ caused the computational model to return to a safer state. The external pressure had to be omitted to obtain the worst-case results of structural analysis. Relevant data is the internal pressure which could be equal to $c_{pi} = -0.4$ cpiaccording to the reference standard. Additional assumptions were made as follows:

— Terrain category 0 → sea and coastal areas at the open sea;
— Wind direction angle 0° → 1.0;
— Wind load zone 2 → $q_{b,0} = 0,42\left[\frac{\text{kN}}{\text{m}^2}\right]$;
— Value z equal to the prefabricated protective dome height (inclusive of the sectional thickness → $z = 5,12[\text{m}]$).

The snow load values were adopted per the Eurocode [8]. The following computational assumptions from [8] were applied in the analysis:

— Specific snow load on the ground in Snow Load Zone 2;
— Thermal coefficient value → $C_t = 1,0;$
— Exposure factor value for the land shielded from the wind, → $C_e = 1,2.$

Case (II) from [8] was adopted to determine the roof shape factor and the snow load on the prefabricated protective dome was determined.

The explosion impulse load was adopted from the highest explosion endurance class per [5], classification code EXR5, explosion of 20 kg of TNT 4.0 m away. The procedure published in [4] was applied to determine the explosion impulse load from an external explosive charge [4]. The functions of pressure change versus time per [4] were determined with the procedure. To properly include the loads in the computational model, each determined pressure change value $\Delta p(t)$ was multiplied by the width of the prefabricated module.

A combination of the following effects was required as recommended in the procedure from [6]:

— basic effects;

$$\sum_{j\geq 1}\gamma_{G,j}\cdot G_{k,j}\text{"}+\text{"}\gamma_{Q,1}\cdot\Psi_{0,1}\cdot Q_{k,1}\text{"}+\text{"}\sum_{i\geq 1}\gamma_{Q,i}\cdot\Psi_{0,i}\cdot Q_{k,i} \tag{5.1}$$

$$\sum_{j\geq 1}\xi_j \cdot \gamma_{G,j} \cdot G_{k,j} \text{"+"} \gamma_{Q,1} \cdot Q_{k,1} \text{"+"} \sum_{i\geq 1}\gamma_{Q,i} \cdot \Psi_{0,i} \cdot Q_{k,i} \tag{5.2}$$

— for a special computational situation (explosion effect).

$$\sum_{j\geq 1}G_{k,j} \text{"+"} A_d \text{"+"} (\Psi_{1,1}\, lub\, \Psi_{2,1}) \cdot Q_{k,1} \text{"+"} \sum_{i\geq 1}\Psi_{2,i} \cdot Q_{k,i} \tag{5.3}$$

5.3. Distribution of internal forces

The solutions of three types of standard combinations provided the worst-case results in combination 3 (the special computational situation: explosion effect), which were qualified for further analysis [3].

The following illustrates the distribution of internal forces in the Form Type 1 module subject to the highest efforts (per 4.2a): bending moments, transverse forces, and axial forces, see Fig. 5.2.

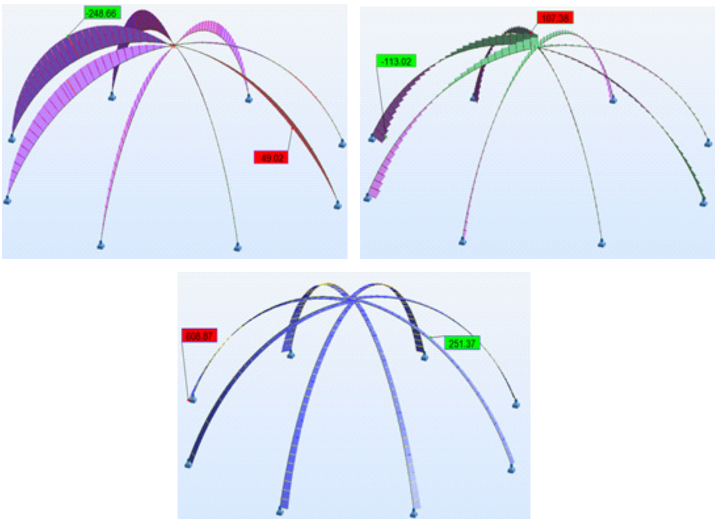

Fig. 5.2. Charts of internal forces: (a) bending moments [kNm]; (b) transverse forces [kN]; (c) axial forces [kN]; [3]

5.4. Dimensioning of the reinforcement

The reinforcement of Form Type 1 modules was dimensioned according to the determined distributions of internal forces and the design procedure specified in [10].

Two computational situations were identified during the dimensioning and selection of reinforcement due to the progression of bending moment variability. It was necessary to select the maximum (top and bottom) reinforcement from the derived results to determine the final general result. The results of reinforcement dimensioning for Form Type 1 modules include the quantity and diameter of the rebars, the minimum concrete cover, and the two identified computational situations; see Table 5.2. The data facilitated a reinforcement structural drawing as shown in Fig. 5.3.

Table 5.2

Form Type 1 module reinforcement [3]

	First computational situation	II computational situation	**Final result**
Top reinforcement	7 ∅10 every 24[cm]	11 ∅20 every 13[cm]	11∅20 every13 [cm]
Bottom reinforcement	7 ∅12 every 25[cm]	7 ∅10 every 25[cm]	7∅12 every 25 [cm]
Ligatures	∅8 every 14 / 24[cm]		∅8 every14 / 24 [cm]
Minimum concrete cover	$d_1 = 60$[mm] $d_2 = 60$[mm]		$d_1 = 60$ [mm] $d_2 = 60$ [mm]

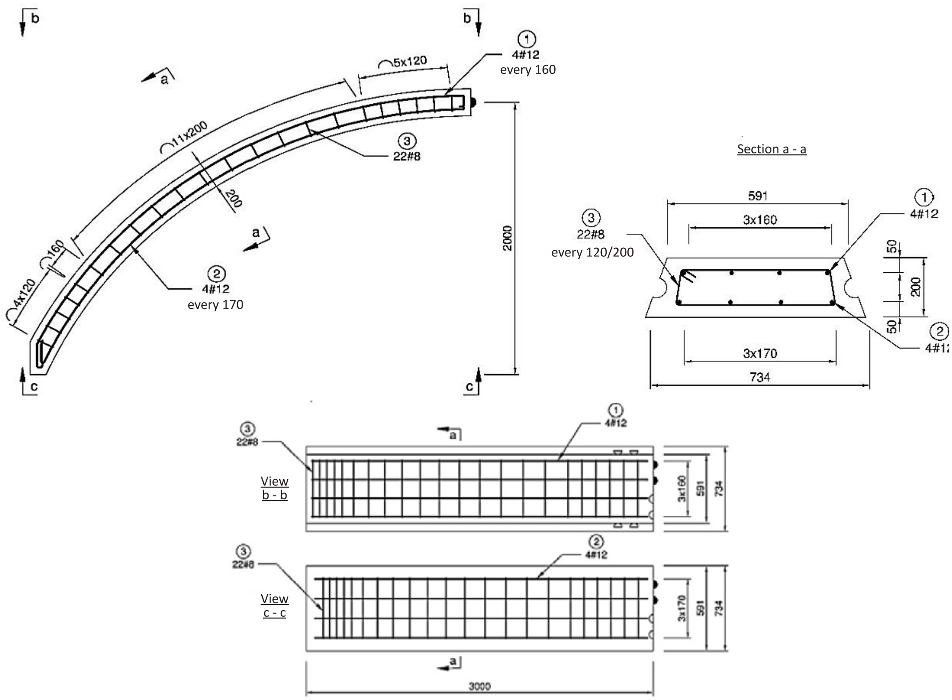

Fig. 5.3. Form Type 1 module structural reinforcement [3]

6. Conclusion

The paper presents the concept of a protective structure formed by a medium-sized dome comprising prefabricated reinforced concrete modules. The form of the protective structure being a dome provided relatively low cross-sectional height values, resulting in the relatively low weight of the modules, which endowed them with improved mobility. The system of 32 prefabricated modules in five different basic form types, see Fig. 4.2a (instead of a cast-in-place construction process) and the concept of joining sockets for the assembly of the protective structure enables reusability by repeated assembly and disassembly.

A numerical analysis was completed to determine the maximum internal forces. The analysis included standard load conditions and the load combinations required by ultimate load capacity states. The dimensioned protective structure could withstand the explosion impulse from a 20 kg charge of TNT, detonated 4 m away, which was assumed as the worst case of EXR5 in [5].

This paper will be followed by a design engineering analysis of the prefabricated foundations for the protective structure and the protective structure itself with erection openings, e.g. inspection hatches in the protective structures deployed around tanks, or access doors for the vehicles to be sheltered.

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K. SOBCZYK, R. CHMIELEWSKI, K. DUDA

Propozycja konstrukcji prefabrykowanej do ochrony obiektów infrastruktury krytycznej

Streszczenie. W artykule przedstawiono propozycję konstrukcji ochronnej, w postaci prefabrykowanej kopuły żelbetowej, do ochrony obiektu infrastruktury krytycznej [1]. Możliwość wielokrotnego montażu i demontażu tej konstrukcji, zamiast możliwej do zastosowania jednokrotnego konstrukcji w technologii monolitycznej, zapewnia użycie specjalnych gniazd połączeniowych. W celu zapewnienia dużej mobilności proponowanego rozwiązania przyjęto wymiary pojedynczych elementów spełniające wymagania dla transportu mieszczącego się w wymiarach skrajni drogowej. Numeryczna analiza obliczeniowa pozwoliła na wyznaczenie rozkładu sił wewnętrznych w konstrukcji oraz na zwymiarowanie wymaganego zbrojenia [3]. W obliczeniach tych zastosowano normatywne przypadki obciążeń stałych i zmiennych oraz ich kombinacje, uwzględniając parametry dynamicznego obciążenia impulsem wybuchu.

Słowa kluczowe: budownictwo, konstrukcja ochronna, kopuła prefabrykowana
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